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COMPARISON OF THE TAKE-OFF AND LANDING PERFORMANCES OF JET - AND FAN- VTOL-AIRCRAFT

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ABSTRACT. The demand for fast aircraft which could take off and land vertically led to a variety of types of aircraft. Whereas the advantages and disadvantages of the individual models are discussed particularly the arrangement of the engines, no comparison has been made so far of the values really attained by means of computations of wind tunnel measurements and flight tests. The investigations dealing with the performance of the different models during take-off and landing are presented. N70-23222#.

1. Purpose

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The goal of a vertical take-off is as old as the documented development of air navigation itself. Leonardo da Vinci drew a sketch of a helicopter as early as 1483. The principle of a vertical take-off using a large propeller has led to the development of successful helicopter models during the past thirty years. Thus, in this sense, VTOL-aircraft have been around for a long time. However, they do not have the necessary airspeed for many purposes. The goal of attaining a very high velocity has finally led to the development of VTOL-aircraft equipped with jet engines and which use the jet streams from these engines for take-offs and landings. In order to solve the problem, many different types of models were investigated, the most successful of which have already been frequently listed in the pertinent literature, e.g. very concisely by G. Gabrielli in [1] and [2].

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* Numbers in the margin indicate pagination ir the foreign text.

A large amount of the extremely technical literature on the problems of VTOL-aircraft has been compiled by G. Bock in a two-volume bibliography [3]; other, recent works are given in the list of references appended to this report. The subject literature treats basic problems, as well as a number of individual questions which had to be resolved in the development of VTOL-aircraft. What was still missing was a comparison of previous results from calculations, wind tunnel measurements and flight tests. This is the purpose of this report.

The completion of this project was only made possible by the fact that manufacturers of aircraft models Do 31 E and VJ 101 C were kind enough to make their data available. We extend our sincere gratitude to these companies. The wind tunnel measurements for model VAK 191 B had already been published in the subject literature. The data on the British VTOL-aircraft, Short SC 1, Hawker-Siddeley P-1127 and Kestrel FGA-MK 1 were also available for purposes of comparison. Comparable figures were also available on the American VTOL-aircraft Ryan XV-5a.

2. Symbols /8

G	Weight of the aircraft (kp)
A	Lift (kp)
W	Resistance (kp)
S	Engine thrust for vertical take-off (kp)
F	Wing surface (m^2)
F*	Cross-sectional area of jet stream
b	Wing span (m)
H	Clearance between wing and ground (m)
h	Clearance between underside of fuselage and ground (m)
T	Time (sec)
g	Acceleration due to gravity (m/sec^2)
ρ	Atmospheric density ($kp\ sec^2/m^4$)
q	Dynamic pressure [$= \rho/2\ V^2$] (kp/m^2)

c_A	Lift coefficient
c_W	Resistance coefficient
V	Overall airspeed (m/sec)
V_∞	Velocity of streamline flow (m/sec)
V_{Str}	Velocity of jet stream (m/sec)
V_A	Speed of full aerodynamic flight (km/hr)
w	Climbing speed
α	Wing angle of attack (°)
ϑ	Longitudinal inclination of the aircraft (°)
η_{Kl}	Angle of flap deflection (°)
$\xi_{r,\ l}$	Angle of aileron deflection, right and left (°)
σ	Direction of jet with respect to longitudinal axis of aircraft (positive to the rear and down)
ϵ	Beam loading = S/F*

3. Necessary Extra Thrust /9

In order to take off vertically, the mass of the aircraft must be accelerated vertically, and the aerodynamic drag in this direction must be overcome. The ratio of vertical thrust to weight is the decisive factor for this type of movement.

The aerodynamic drag of the aircraft at slow initial speeds is very low in a vertical direction, as all rough calculations show (numerical values given in Section 4.1).

However, the forces necessary for acceleration (take-off) and deceleration (landing) which are based on the mass of the aircraft and the aerodynamic drag are not the only ones which must be considered when selecting the extra thrust. There are a number of other factors which must be taken into account. The most important ones can be classified into four groups (3.1...3.4) which will be discussed subsequently.

3.1. Purpose of the Aircraft

The purpose of the aircraft is very important for the selection of the extra thrust. As can be seen from Figure 1 [4], a multijet transport aircraft should have a greater extra thrust than a tactical aircraft. The reason for this is that it is possible to land a transport aircraft even if one of its engines fails, whereas a VTOL-tactical-aircraft is usually considered lost if an engine fails while the craft is in flight. (The crew can escape by using the ejection seats).

The extra thrust must also be large enough so that a vertical take-off and landing are guaranteed in test flights which are appropriate for the purpose of the aircraft even under abnormal atmospheric conditions. The maximum attainable engine thrust depends on the condition of the surrounding air, and when the extra thrust is very small, it is impossible to take off or land vertically when the atmospheric density is low. High atmospheric temperature as well as low atmospheric pressure have unfavorable effects in this case. The results of considerations in this regard are represented graphically in Figure 2. (Cf. [5]). In this case, the effect of the changes in the atmospheric density up to altitudes of approximately 1,500 m is taken into account. Similar factors are taken into consideration in [6].

3.2. Thrust Loss Resulting from Aircraft Configuration /10

Figure 2 indicates other factors which reduce thrust. Inasmuch as the effects of these factors cannot be eliminated through specific types of take-off techniques, they must be taken into account when selecting the extra thrust so that a ratio S/G > 1 is guaranteed and a vertical take-off is always possible.

The following factors which unfavorably affect the development of thrust will be discussed in detail: the so-called recirculation, the intake losses, the rotational losses and the losses which result from drawing off compressed air, insofar as jet control is necessary in hover and transition.

3.2.1. Recirculation

Depending on how the jet stream runs in relation to the fuselage, wings and tail plane, a greater or lesser amount of the hot exhaust is deflected off the ground and sucked in by the jet aircraft engine. Diregarding the dust which is carried along with it, heated intake air (as already mentioned in 3.1) causes the thrust to decrease. For this reason, in all wind tunnel measurements which are made on all new designs, it must be determined whether the jet stream is directed at a favorable or unfavorable angle. Figure 3 [7] shows the flow field measured by the manufacturer on model Do 31 E on the ground. When measurements of this type are made (scale in this case 1:20) the question arises to what extent wind tunnel measurements are applicable to actual flight conditions. The manufacturer stated that wind tunnel measurements and actual conditions correspond sufficiently with respect to order of magnitude. The Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt is in the process of carrying out thorough investigations at the Institut fuer Strahlantriebe in Braunschweig which deal with the problem of recirculation along with other ground effects, and also intends to subsequently issue model laws for them [8]. Recently, the following methods have been used on finished designs to deal with the problem of recirculation: first of all, when there is a very fast vertical take-off, there is no

time for the flow field to develop, and secondly, the flow field remains behind the aircraft if it does not take off in an exactly vertical direction, but rather assumes a forward velocity immediately after lift-off. If necessary, a short taxiway can be included for this reason. And /11 finally, metal sheets can be situated on the ground to act as jet deflectors if the aircraft must take off from a surface other than a runway.

3.2.2. Intake Losses

The approach flow direction and the flow velocity at the engine intakes change in the case of a vertical take-off, and in the subsequent transition to full aerodynamic flight. This produces the so-called intake losses of the engines. Attempts are made to keep these losses at a minimum by modifications in the design of the air scoops (often with adjustable, controllable cross sections), but it is not always possible to guarantee favorable intake conditions for all jet engines under all flight conditions. This is especially true in the case of a vertical landing, where the downward motion of the aircraft has an unfavorable effect on the ingestion of the engine. Numerical values for the intake losses for the special case of design VJ 101 C are given in [9].

3.2.3. Rotational Losses

In many aircraft designs, e.g. VJ 101 C - X1 the total thrust must be used for a vertical take-off by rotating the engines. In other models, e.g. Hawker P-1127, the thrust is from the vertical to the horizontal flight attitude by means of rotating nozzles. The nozzles are located in this case on the sides of the fuselage, and the jet stream must be rotated for both the above-mentioned flight attitudes (and

for all intermediate attitudes. The thrust therefore becomes less. The manufacturing firms figure this loss at 3%.

3.2.4. Thrust Loss for Steering

A distinction is made between VTOL-aircraft which effect movement about the three major axes by changing the magnitude or direction of the engine thrust (thrust modulation), and those which accomplish this by using compressed air which is discharged from jets mounted specifically for this purpose. The intermittent or contant drain of compressed air from the engine causes thrust losses. A comparison of the thrust losses in the case of steering via thrust modulation and in the case of discharged air is given in [10]. Under the given conditions, steering via thrust modulation is essentially better as regards thrust losses.

3.3. Effect of Ground Level /12

The magnitude of the extra thrust is also important for the following processes in the immediate vicinity of ground level.

3.3.1. Ground Erosion

When the hot exhaust from a jet engine hits the ground immediately after it is discharged, it can damage loose ground. For this reason, afterburners cannot be used in VTOL-aircraft without taking special precautions. If metal grids or other types of ground protectors are used, then a primary advantage of VTOL-aircraft - employment on all types of terrain - is lost, at least from a military standpoint.

The anticipated ground erosion is certainly no criterium for measuring the S/G ratio, but it must be taken into account in the choice of the engine (because of its jet

velocity) and in the arrangement of the engines on the aircraft even as early as in the design stage.

Extensive tests on ground erosion were carried out using the Hawker P-1127 design. Since it is rather cumbersome and expensive to use airplanes for these tests, Dornier Inc. developed a mobile testing stand. A jet engine can be mounted and swivelled on the trailer of a truck in such a way that its jet stream strikes the ground from different altitudes and at different angles [11].

3.3.2. Ground Effect and Necessary Extra Thrust

The graph in Figure 2 also takes into account that part of the vertical thrust can be lost because a vacuum is created under the airplane by the ground effect, and this counteracts the vertical thrust. This fact has been recognized for a long time (cf. e.g. [12]). The aircraft configuration and the arrangement of the engines can also have a favorable effect on vertical take-off. Figure 4 shows two opposing cases. In the upper sketch, an undesirable vacuum is created under the wings by the jet streams, whereas in the lower sketch, which is approximately the same as model VJ 101 C, the jet streams meet to produce a force in the desired direction under the fuselage. Figure 4 represents only schematically two different possibilities; actually, the processes are much more complicated since the shape of /13
the flow field depends on the distance between the airplane and the ground, on a possible longitudinal or transverse slope, on the throttling of the engine and the condition of the ambient air (wind, temperature, density).

Figure 5 gives the results of wind tunnel measurements and a flight test in such a way that, of the many parameters mentioned, at least the distance from the ground is taken

into account by the ratio h/b. (b = wing span of the airplane, h = clearance between the underside of the fuselage and the ground). From the values plotted along the ordinate, it is indicated whether the resulting force for a given value of h/b is directed upwards or downwards. It must be noted, however, that the results of the wind tunnel measurements are stationary values, whereas vertical take-off and landing are actually processes of acceleration and deceleration. Even more important for purposes of comparison is the flight test curve plotted for the P-1127. In this case, it must be noted that we are dealing with values which were calculated for a landing. This means that the curve is not valid for a condition where full engine thrust is used but rather for a ratio of $S/G \approx 1$.

In order to avoid difficulties connected with a vacuum at ground level, the take-off must proceed as quickly as possible (as already recommended in Section 3.2.1 for other reasons), so that the flow field does not have enough time to completely form. In order to escape the region of the ground effect, an altitude of approximately 5 m is sufficient according to [13].

3.3.3. Gusts at Ground Level

The extra thrust must also be sufficient to equalize the effects of gusts during take-off and landing. Let us examine next gusts in a vertical direction. Most gusts at ground level, regardless of their direction, do not last long..For this reason, vertical gusts are not very considerable during take-off when the airplane exhibits an accelerated upward motion. Even a powerful, vertical downdraft will not reverse the direction in which the accelerated airplane

is moving during the short time for which the gust lasts.

Conditions are different in the case of a vertical landing. In this case, the airplane already exhibits a downward movement. If it is influenced by a gust which is directed downward shortly before touchdown, the landing gear may be overtaxed if the engine thrust does not brake /14
sufficiently (rapid engine response is necessary). (The landing gears of VTOL-aircraft must be dimensioned nowadays for vertical descent rates of approximately 4 m/sec.) The following factor is also important for the strength of the landing gear. In the early development stages of VTOL-aircraft, consensus was that VTOL-aircraft landing gears could be constructed with less weight than those of conventional aircraft. During conventional take-offs and landings, the landing gear is subjected to great stress in a horizontal direction, which would not be the case with VTOL-aircraft - so it was thought. In the meantime, however, all successful VTOL-aircraft were designed in such a way, that in addition to vertical take-offs and landings, they could also execute horizontal take-offs and landings.

The extra thrust must also be sufficient enough to counteract changes in the attitude of the airplane which are introduced by gusts with horizontal components. An effect similar to that produced by gusts of air is caused in this respect by the forces which are introduced when the velocity of the jet stream or its direction is changed. Processes of this nature make higher demands on the manuverability of the airplane.

3.4. Extra Thrust Necessary for Reduced Angle of Attack

Whereas some of the above-mentioned problems can be overcome by modification of the VTOL-aircraft (short take-off),

the following problem cannot be solved in this manner. Not only during lift-off, but also during the entire transition, the jet streams which are directed downwards reduce the effective angle of attack. Even this effect depends in great measure on configuration; its magnitude depends on the position of the jet streams with respect to the wings, the fuselage and the tail assembly. The effect may be so great that the extra thrust must be selected by considering only the lift loss and not from the above-mentioned points of view. This lift loss results from the induced angle of attack.

Figure 6 gives four examples based on wind tunnel measurements, which show how great the effect in question can be numerically. When comparing these examples, it must be taken into account that the angle of flap deflection was 0° on only two models. It is evident from the curves why VTOL-aircraft take off with extended flaps. All the examples in Figure 6 correspond to a ratio of the velocity of the streamline flow V_∞ to jet stream velocity V_{Str} of /15 approximately 0.2 (an average value in transition). The effect of the jet streams on the effective angle of attack depends very heavily on the ratio of V_∞/V_{Str}. For this reason, the results of wind tunnel measurements are given in Figure 7, and from these results, we can see the effect of V_∞/V_{Str} on c_A. Figure 8 gives the dimensionless value $\Delta A/S$ for different airplane designs and projects on the basis of wind tunnel measurements as a function of V_∞/V_{Str}.

3.5 Engine Failure

The problem of engine failure in multijet VTOL-aircraft is treated in detail in the technical literature.

Special reference is made to [21]. This source gives diagrams which indicate the minimum necessary value of S/G as a function of the number of jets in the design stage which enables the aircraft to land vertically after engine failure. The data in [21] also notes that for many configurations, an engine on the opposite side of the craft must be throttled if an engine fails because of the trim. Source [21], however, does not take into account the fact that many designs (e.g. Do 31) have engines with different thrusts and that the failure of one jet engine can affect the intake (so important in VTOL-aircraft) of the other engines.

Companies which at the present time are manufacturing VTOL-aircraft have experience with these effects and with those mentioned in preceding paragraphs which result in loss of thrust. Thus, today, when a new VTOL-airplane is designed, it is clear from the very beginning whether the craft must be abandoned in case of engine failure, or whether it can continue flying and land vertically or at least land conventionally.

3.6. Vertical Component of Thrust in Transition

The empirical values given in 3.5 are also necessary for preliminary calculations of the take-off and landing performances of VTOL-aircraft which correspond as closely as possible to those made under actual conditions. (Cf. Sections 4.2 and 4.3). The factors mentioned in Sections 3.2.2 to 3.2.4 and 3.4 reduce the thrust and its vertical component in a way which is by no means fully understood. If, however, the transition takes place in horizontal flight, then the vertical component of the thrust must change continuously throughout the transition so that it (after

the vertical acceleration phase) together with the increasing /16
lift (from the aerodynamic forces) always corresponds to the weight of the airplane. Acceleration of the airplane to aerodynamically controlled horizontal flight is effected by the horizontal component of the thrust.

The curve of the vertical component (as well as that of the horizontal component) can be followed very easily e.g. in [20] by means of a concrete example, if the thrust of the individual engines, the angle of incidence of the engines with respect to the longitudinal axis of the aircraft and angle of longitudinal inclination of the aircraft are extracted from the given diagrams.

4. Comparative Considerations

How large then, is the extra thrust in VTOL-aircraft? A quick look back at Figure 2 shows which values are optimum for S/G with respect to the many unfavorable influences which were discussed in Section 3. But even the (necessary) requirement that S > G is difficult if it is compared with the values for S/G of conventional aircraft. Even the supersonic passenger planes such as the Concorde and the Tupolev 144 require S/G values of approximately 0.4 to 0.6 for take-off! (Figure 9). It would be nice to make do with as little extra thrust as possible. The greater the thrust, the greater the engine weight and the space necessary for the engines. If grossly oversized engines are used for cruising, then the sharply throttled engines have an unfavorable specific fuel consumption. The correct distribution of the thrust to the jet and cruise engines is therefore very important for VTOL-aircraft with several engines. These problems have already been thoroughly treated in the technical literature, in which case the safety factor in event of engine failure was also

considered. [14]...[26]. Therefore, the subject will not be touched on again in this report.

The values for the reciprocal thrust coefficient of the major contemporary VTOL-aircraft can be inferred from Table 1. The following must be taken into consideration when dealing with the data in this table. The values for the ratio S/G are arrived at by dividing the thrust indicated by the manufacturer, inasmuch as it is applicable, by the maximum planned vertical take-off velocity. Actually, the ratio of S/G becomes smaller when the thrust losses discussed above come into play. /17

The purpose of the airplane, as already mentioned in Section 3.1, is the decisive factor for the magnitude of S/G. A VTOL-airplane with one jet engine, which must be abandoned in case of engine failure, can make do with a relatively small extra thrust, as long as the possibility of greater vertical acceleration is not required by virtue of its functional applications.

In the case of a transport airplane, e.g. model Do 31, the conditions are different. In this case it is necessary for the equipment to remain in flight after engine failure. For this type of configuration, failure of a cruise engine is especially critical, since these engines also provide vertical thrust for vertical flight. In cases of this sort, a significantly greater value for S/G must be chosen for the initial state. Again, reference is made to the already mentioned diagrams in [20].

In order to maintain a guaranteed take-off weight in airfields at higher altitudes, or at higher temperatures, so-called "flat rated engines" are preferedd, where the thrust is automatically regulated as a function of the altitude and temperature.

4.1 Fuel Consumption

Fuel consumption per unit time of jet- and fan- VTOL-aircraft in hover is approximately eight times that used for cruising. Figure 10, according to [27] shows the fuel consumption for an assumed example (flying weight approximately 18 tons) as a function of the jet velocity. Since the above-mentioned source is based on the (unaccelerated) condition of hover, a value of S/G = 1 must be assumed for the given figures for fuel consumption. In the case of an accelerated vertical take-off, even higher values must be considered for fuel consumption. These are given, e.g. in [7]. The specific fuel consumption as a function of the radiant surface load is treated by G. Gabrielli in [28]. The graphs in Figure 11 are taken from this source. They cover the entire range of radiant surface loads from helicopters to thermal jet-VTOL-airplanes.

If the fuel consumption of this type of VTOL-airplane /18 is calculated using these values, the following is obtained. Whereas a conventional aircraft needs only 0.5 to at most 1% of its fuel supply for take-off and landing (depending on whether it is a long or short distance craft), a jet-VTOL-aircraft needs approximately 10% [7]. Since for some purposes there will be two take-offs and two landings without refueling, the high fuel consumption which is necesaary will considerably reduce the range of this type of plane. Of the above-mentioned ten percent, approximately one fourth is needed for take-off and three fourths for landing. The following example is cited for the P-1127. If the airplane overshoots its landing spot by only 75 m, then the correction maneuvers will consume just as much fuel as the entire transition. Very similar conditions must be assumed for other thermal jet-VTOL-aircraft.

4.2. Time-Optimal Vertical Take-off

Since it is also very important to take off and land in as little time as possible, it was only natural to carry out optimization calculations for these processes. This has been done e.g. by H. Friedl and K. Stopfkuchen [29] and by G. Bruening [30]. The dynamic programming method was used in [29], whereas the Pontrjagin maximum principle was used in [30]. In both cases, many simplifications were necessary before the calculations could be carried out at all. Actually, the many factors discussed in Sections 3.2 and 3.4 have an effect. Up to the present time, they could not be taken into account in time-optimal calculations. For this reason it is understandable why optimization calculations were not carried out using the above-mentioned methods until now.

4.3 Simplified Take-off Calculation

In addition to the efforts to obtain optimization, an attempt was made to numerically describe a vertical take-off from lift-off to full aerodynamic flight in another way. Flying demonstrations (e.g. Farnborough, Le Bourget, Hannover-Langenhagen) showed that the process could be made up of two parts for purposes of simplification: a vertical part and a subsequent horizontal part. In the second part, the airplane was accelerated to that speed at which the lift was equal to the weight. A similar simplification in which the flight path of an airplane taking off in the conventional way is divided into two straight lines can be found in [31]. /19

4.3.1. Pure Vertical Movement

The equation for climb is based on the thrust which is available for vertical acceleration:

$$\frac{G}{g}\frac{dv}{dt} = S_{vertical} - G - W_{vertical} \qquad (1)$$

As regards the magnitude of the vertical thrust, it is assumed that all initially mentioned factors have already been taken into account.

The drag of the airplane W_v in a vertical direction is small during the first seconds because of the relatively slow speeds. For the example studied in [29], Figure 12 gives the numerical difference which results from the aerodynamic drag with respect to time as the craft climbs to a specific altitude. Other subsequent calculations yielded similarly small differences for other examples. Figure 12 also shows the difference in time which results when the flight path of the craft assumes a horizontal tangent at the end of its climb. By diregarding the drag (permissible for rough calculations), the equation at (1) yields values which are plotted on the graphs in Figure 13. The already known measurement values from VTOL-aircraft confirm the usefulness of Figure 13 for rough calculations and comparisons. Using the curves in this figure, the vertical thrust which is actually present during take-off can be approximated. Thus, inferences are possible on the total magnitude of the factors mentioned in Sections 3.2 to 3.4 which reduce the thrust in the first seconds after take-off. The large amount of influencing factors makes individual approximation difficult.

4.3.2. Horizontal Movement

The vertical climb discussed in the preceding section is followed by horizontal movement. The force to accelerate the airplane in a horizontal direction results from a reduction of the engine thrust by the aerodynamic drag and the drag when taxiing in the case of a conventional landplane [31].

$$\frac{G}{g} \cdot \frac{dv}{dt} = S_{horizontal} - W - R \qquad (2) \qquad /20$$

This equation is simplified in this case by the fact that the drag when taxiing, R, is left out. As regards the horizontal thrust, it can be considered constant for some VTOL-aircraft during the relatively short take-off time, if we are dealing with jet engines. This point of view, however, is only permissible for those types of VTOL-airplanes in which the jet engines deliver only vertical thrust and the cruising engines only horizontal thrust, as is the case e.g. with the Short SC 1, Dassault-Balzac and Dassault-Mirage III V.

But even for these three models, for which there are some measurement values which can be compared with the calculation (VJ 101 C - X1, P-1127 and Do 31 E), the conditions for the thrust curve during take-off are quite different and vary among themselves. In none of these cases can the thrust available for horizontal acceleration be considered constant in transition.

In the case of the VJ 101 C, the shift in the thrust for the cruising engines is accomplished by hydraulic adjustment of the engine pods. The thrust curve of the jet and cruising engines in transition is given in [20]. In the British model P-1127, the thrust from the individual jet engines is gradually shifted to the rear by means of rotating jets, so that there is always a great enough vertical thrust remaining to prevent a loss of altitude before the craft attains full aerodynamic flight. In model Do 31 E, the necessary horizontal thrust in transition is delivered primarily by the cruising engines, the thrust direction of which can be changed by means of rotating jets as with the P-1127. The jet engines can be swivelled 15° to the front and to the rear, but the horizontal thrust component produced in this case is naturally very small.

Using the data which was available on these processes, the respective thrust curve was made the basis of further calculations. In order to carry out simplified take-off /21 calculations, assumptions had to be made about the coefficient of drag during horizontal flight. As regards the case of the conventional take-off examined in [31], there was no doubt that the drag coefficient when taxiing can be considered a constant (undercarriage extended, flaps down to one third of maximum, ground effect practically constant). When a VTOL-aircraft shifts from hover to full aerodynamic flight the conditions are different.

The take-off instructions for a British VTOL-airplane describe the vertical climb with full flaps as follows. After beginning horizontal flight, the undercarriage is retracted and the flaps raised so that the angle of deflection is zero, when the forward speed is between 90 and 280 km/hr. Since, however, a rather large wing angle of attack (> 10°) will correspond to the minimum permissible, aerodynamically controlled speed in horizontal flight after the flaps are raised, the coefficient of drag, based on examples, must be selected relatively large. If the term "transition" means the shift from hover to full aerodynamic flight, then the coefficient of drag will be large at the start of transition because of the extended undercarriage, and the flap deflection. At the end of transition, the value will not be much smaller because of the angle of attack which is appropriate for the minimum permissible speed. Special types of airplanes, egg. model VJ 101 C, which must begin horizontal flight with the cruising engines almost vertical (at the wing tips) [20], will naturally have special problems regarding drag. (Cf. Section 4.4.).

Obviously, the manufacturers have wind tunnel measurements from which the coefficients of drag in transition can be taken. Only few measurements of this ilk can be found, however, in the technical literature. For model VAK 191 B, the effect of the jet streams on the values of c_A, c_W and c_M are given in [32] and [33]. This effect is, as expected, a function of the ratio of the velocity of the streamline flow to the jet stream velocity, as well as a function of the angle of the jet stream with respect to the longitudinal axis of the airplane. Figure 14 shows the polar curves of the VAK 191 B with and without the effect of the jet streams. Using the /22 curves, an average value can be obtained for the coefficient of drag in transition. The same order of magnitude for the increase in resistance can be obtained from the curves for model Do 31 E, which is given in Figure 14, right. The difference in the basic polar curves for both models results from the great difference in the aspect ratio of the wings.

4.4. Comparison of Measured and Computed Values

Mention might be made here of the fact that only very few flight test results have been published up until now. Especially for German models, there are no values which could be claimed as optimal values (as regards take-off or landing time). A very thorough series of flight tests has been carried out on the British model P-1127. The test values obtained in this case differ greatly, which is certainly caused by the novelty of the equipment and the large number of influencing factors (compare Sections 3.2 to 3.4). For a comparison of measured and computed transition times, it would be best to consider primarily the optimal values, since poorer values are probably caused by a combination of unfavorable factors or even by the lack of experience on the part of the pilot alone.

In comparing the test values from different model aircraft, it must be remembered that different testing and measurement techniques may be responsible for certain differences.

Figure 15 contains both measuring points and values for the British model P-1127. These were calculated using the methods discussed in Sections 4.2 and 4.3. The results of computations which were plotted on a graph refer to the time between lift-off and the time when an altitude of 15 m is reached (Curve a) and to the time between lift-off and full aerodynamic flight (Curve b) as a function of the reciprocal thrust load. Considering the simplified assumptions for the calculation, the correlation between test values and the results of the calculations is satisfactory.

In the case of model Do 31 E, the only previously published measurement value [7] was selected as the basis for the calculation. In this case, it must be mentioned that the flight measurement is based on a take-off where a forward movement immediately succeeds the vertical lift-off (Figure 16).

An essentially different type of take-off is required /23
for model VJ 101 C because of the aircraft configuration. After a vertical climb to an altitude of approximately 25 m [20], the engines on the wing tips are swivelled automatically so that the horizontal thrust vector becomes increasingly greater and accelerates the craft to full aerodynamic flight. The thrust curve for the cruising and jet engines is given in [20]. Since the aerodynamic drag changes significantly when the cruising engines are rotated, the calculation was done using three different drag coefficients. (Compare Figure 17).

In a comparison of the times which individual VTOL-aircraft require to pass from lift-off to full aerodynamic flight, the values in Figure 18 for model VJ 101 C are conspicuous. The following must be noted in this case. Whereas in the case of other VTOL-aircraft, the pilot is not bound to a set schedule when rotating the thrust vector during take-off, but can control the speed of rotation by means of a rocking lever, the thrust shift in the VJ 101 C is accomplished by means of an hydraulically controlled rotation schedule. This makes sure that the ratio of thrust to weight does not drop below 1. The rotation schedule must also take into account the flow conditions at the air intake scoops of the engines mounted on the wing tips. Security reasons also played a part in determining the speed of rotation for the first airplane from this design. In the subsequently selected schedule adjustment (Figure 18, upper curve), the schedule yielded a mean rate of rotation for the cruising engines and their pods of 1° per second during the first thirty seconds of transition. In the second part of the transition, the pilot switched to a faster rate of rotation, which, according to the schedule, yielded an average value of 4° per second. Since rather large transition times were obtained in this way, the rotation schedule was changed [34]. Thus, it was possible to reduce the time required to achieve full aerodynamic flight from 55 to 45 seconds under otherwise equal conditions.

For all VTOL-aircraft, the problem of as brief a landing transition as possible is an even more difficult one that that of a short take-off. Touchdown must take place at an exact point with a very slow rate of descent. During the entire transition, the pilot must make sure that he does not overshoot his target point. Correction maneuvers after

missing the intended landing point are troublesome and, /24 as mentioned in Section 4.1, consume a large amount of fuel, which may already be in short supply at the end of the flight. The problems involved in a vertical landing can be clearly seen in Figure 19. No curves can be derived from the measurement values in this case; the distribution of the values is too great for this. But one thing can be clearly seen from Figure 19: the advantage offered by an automatic descent governor. A reduction in the landing time from approximately 50 to approximately 30 seconds is obtained from the times measured with only a stopwatch on the Short SC-1. The necessity of an automatic descent governor is also referred to in [7]. This is an important point in the further development of VTOL-aircraft.

4.5. Flight Paths of Different VTOL-Aircraft During Take-off and Landing

As can be seen from the preceding, attempts to develop a functional VTOL-airplane have yielded different solutions. None of the VTOL-airplanes for which measurement results have been published has the same configuration as the aircraft designs of other companies. Although in this respect, there is no common basis for comparison, the flight paths of five VTOL-airplanes have been compiled in Figure 20. In addition to the ideal paths of the VJ 101 C (according to [20]) and the Ryan XV-5[a] (according to [35]), the curves for the Short SC-1 (according to [36]) and the Do 31 E (according to [7]) show how a take-off is effected for such different configurations on the basis of the manufacturer's considerations. The curve for the Hawker P-1127 has been plotted using the take-off instructions for this aircraft.

In order to examine the take-off process more exactly, the increase in weight to full aerodynamic flight was plotted in Figure 21 as a function of the times for the five models. Using this mode of representation, the curves are divided into two groups. The three models, P-1127, Short SC-1, and Do 31 E, reach full aerodynamic flight in 25 to 30 seconds. The Ryan XV-5a and VJ 101 C require more time for this process. The reasons responsible for this in the VJ 101 C have already been discussed in Section 4.4. The longer time required by the Ryan XV-5a is a result of the fact that the transition from hover using the wing blower wheels to horizontal flight with direct jet propulsion takes place only gradually. (Adjustment of the blower exhaust grid, control /25 of the engine rate of rotation, adjusting the flaps behind the engines).

The same relationships given in Figures 20 and 21 for take-off were also studied for VTOL-aircraft landings. Landing, as already mentioned, makes more demands on the pilot than does taking off. This fact is also represented in the curves in both the following figures. In Figure 22, the difference between the optimal flight path calculated and that chosen by the pilot in the flight test of the Do 31 E, discussed by F. Hoffert in [7], is especially noteworthy. From the track curve of the Short SC-1 it can be seen how hard the pilot was trying not to overshoot the target point [36]. The straight-line flight paths given by other manufacturers are not based on flight measurements. Landing paths which are possible for VTOL-aircraft with ground control when the visibility is low are described in [37]. (Compare also [38]).

Finally, Figure 23 shows the deceleration as a function of the time before touchdown. It is amazing that the many factors mentioned earlier which are of importance in a vertical landing do not have a greater effect on the constant course of the curves in Figure 23. During this type of landing, the ratio of V_∞/V_{Str} (compare e.g. [39]) changes continuously, and even the factors which were not followed for the reasons initially mentioned in this report, are functions of the attitude and power of the jet streams.

5. Summary

/26

Based on wind tunnel measurements and flight tests for which data was available, calculations were carried out and the performances of VTOL-aircraft during take-off, landing and in transition were compared. The VTOL-aircraft for which the necessary data were available differ not only in their purposes, but also in their external design and the arrangement of their jets. This explains the rather great differences which were apparent during take-off and landing of the different models. Nevertheless, the studies and the graphs produced give a survey of the order of magnitude of the differences resulting from the different configurations of design. The subject of further comparative studies is the influence of factors which are generated by the jet streams during take-off, landing and in transition.

This report examines only the take-off and landing performances of jet- and fan- VTOL-aircraft. As important as the take-off and landing processes are for a VTOL-airplane, this does not mean that airplanes, which perform well in these areas as a result of their configuration (compare Sections 4.4 and 4.5 of this report), are generally suited for their purpose.

The suitability of a VTOL-airplane for a specific purpose depends on other important factors besides take-off and landing performance (as is also true of conventional airplanes). We mention here only the following: maximum and cruising speeds, useful load for a given range, the ceilings, and, what is extremely important, good maneuverability in all possible flight attitudes. In addition, the ceiling at hover, and the permissible duration of hover with respect to the fuel supply (and thus, with respect to the range) is especially important for VTOL-aircraft.

All these viewpoints have been treated in detail by AGARD in [40]; this source also lists in survey form the advantages and disadvantages of the different types of VTOL-airplanes.

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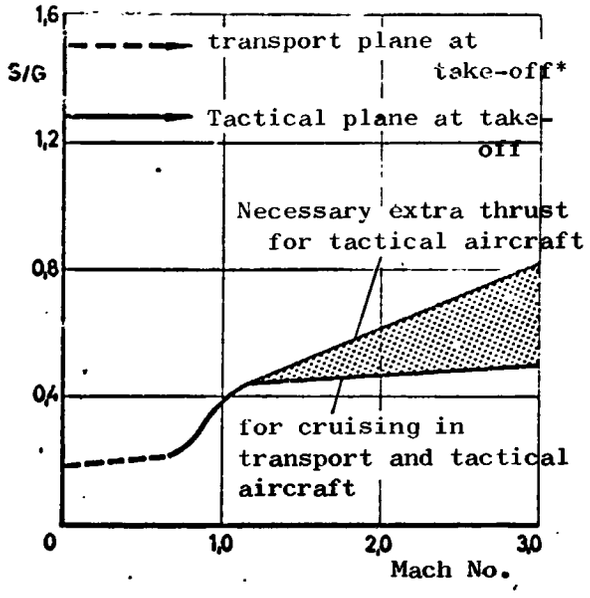
TABLE 1. DATA OF IMPORTANT VTOL AIRPLANES

Aircraft design	First hover	Weight, G, for vertical take-off kp	Thrust, S_V, for vertical take-off existing in theory, kp	S_V/G	Wing surface F, m^2	Surface load G/F, kp/m^2	Remarks
Short SC-1	1954	3650	4x966 =3864	1.06	19.7	185	In addition a cruising engine of 966 kp thrust
Hawker P-1127	1960	5630	6895	1.22	17.3	325	Direction of thrust changeable by curved duct thrusters at side of fuselage
Dassault "Balzac"	1962	7000	8x1000 =8000	1.14	27.2	258	Additional cruising engine with 2200 kp thrust. Weight at take-off planned 1962 G=6100 kp
VJ 101C-X1	1963	6000	6x1250	1.25	16.1	373	Mach number reached, 1.08
Dassault Mirage III-V	1965	13440	8x1850 =14800	1.10	36.6	367	Additional cruising engine with 8400 kp (with afterburner). Mach number 2.04 was reached on 12 Sep 66. No further construction planned.
Hawk.-Sidd. "Harrier"	1966	7260	8710	1.20	18.7	390	Over 60 under construction for the RAF
DornierDBo 31E	1967	22500	2x6150=12300 8x1865-14920	1.21	57.0	395	Cruising speed 650 km/h at altitude of 6 km Cruising speed 500 km/h at altitude of 0.3 km

TABLE 1. CONTINUED

Aircraft design	First hover	Weight, G, for vertical take-off, kp	Thrust, S_V, for vertical take-off existing in theory, kp	S_V/G	Wing surface F, m^2	Surface load G/F kp/m^2	Remarks
Dornier Do 131A	-	37630	2x5650=11300 14x2720=38080	1.31	88.0	427	Cruising speed 850 km/h
VFW 191 B	-	7000 to 9000	2x2720 1x4610	1.43 1.12	12.5	560 to 720	It is planned to build only three airplanes. Cruising speed near the ground is in high subsonic range.

Sources: (1), (2), (7), (8) and (9) according to Jane's AWA 1967/68; (9) also according to Interavia, Vol. 22, No. 9, 1967, pp. 1377-1881; (4) according to Jane's AWA 1966/67; (3) and (5) according to Euroavia News, No. 4, 1966, pp. 1-4; (6) Interavia, Vol. 23. No. 3, 1968, pp. 336-338 and Flugwehr und -Technik, No. 3, May/June, 1968, pp. 84-86.



* E.g. Project Do 131 B; such high values for S/G are obtained for VTOL-aircraft with multi-jet arrangements by taking into account a case of engine failure.

Figure 1. Necessary extra thrust depending on the purpose of the model, according to [4]

(Commas represent decimal points)

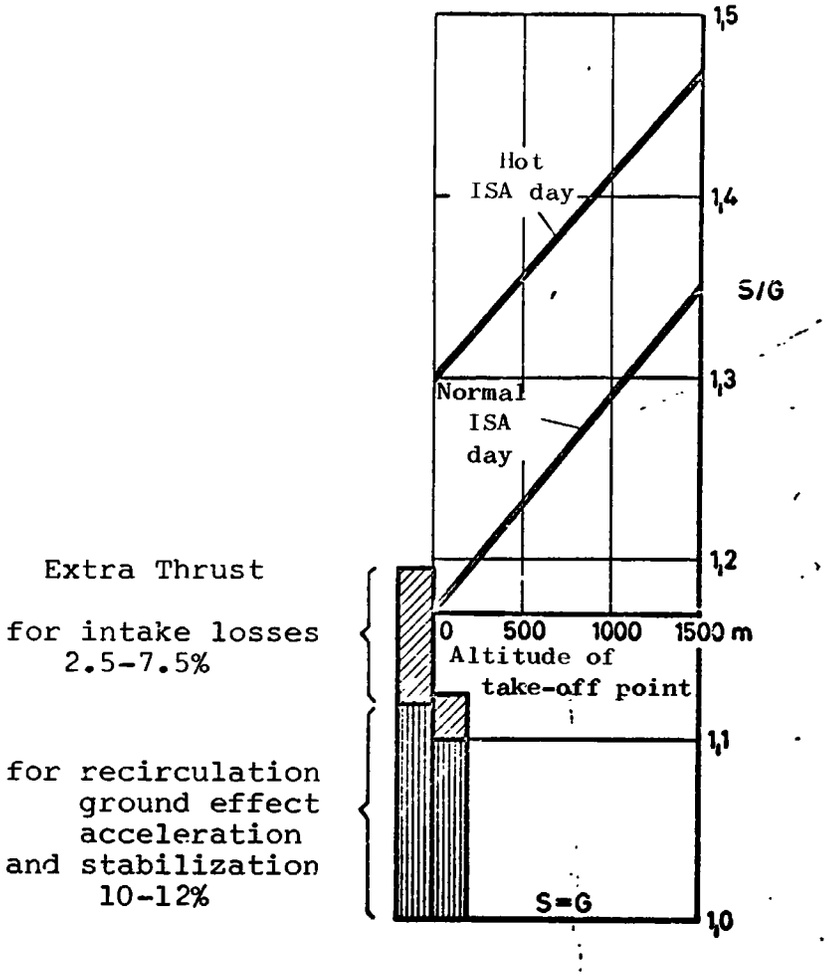


Figure 2. Necessary thrust with respect to thrust losses according to [3]

(Commas represent decimal points)

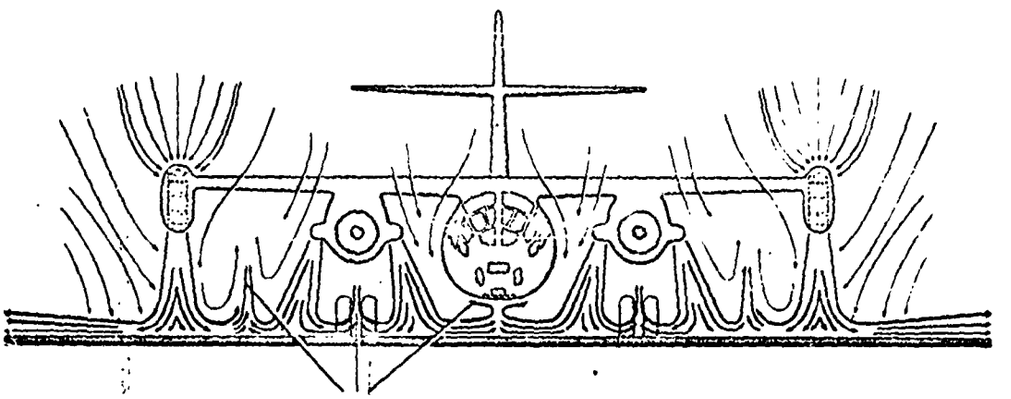


Figure 3. Flow field of Do 31 on the ground according to [7]

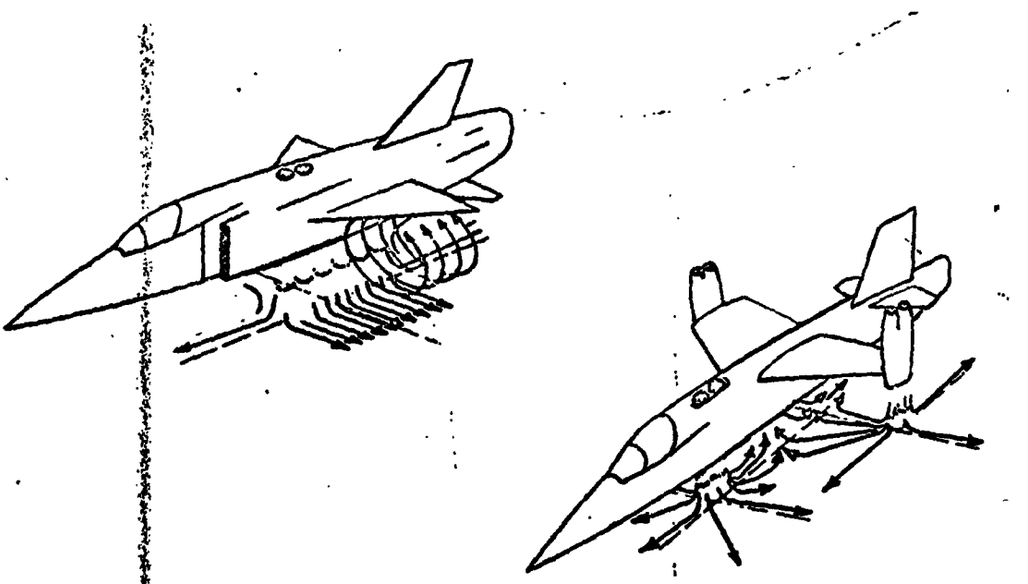


Figure 4. Favorable and unfavorable effect of the jet streams on the lift according to [20]

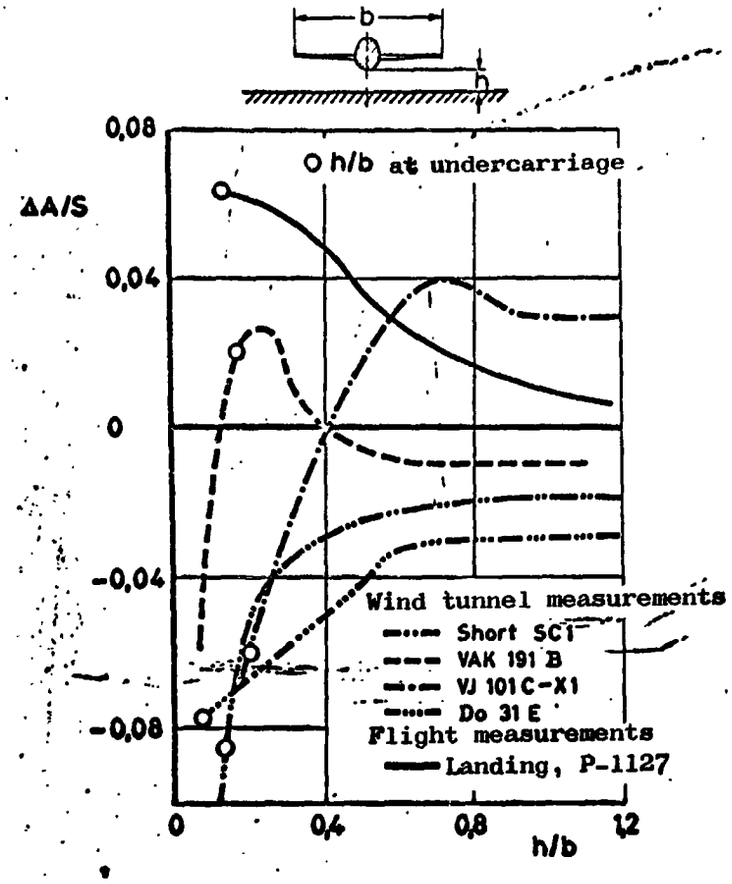
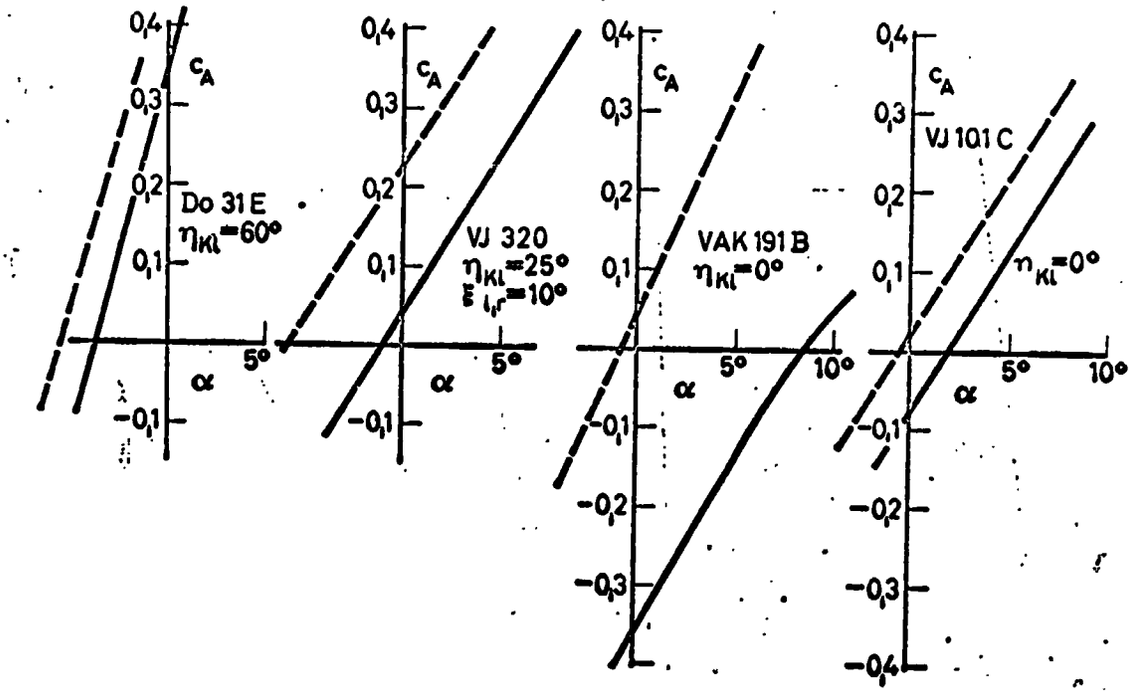


Figure 5. Jet effect at ground level
(Commas represent decimal points)



All values of $(V_\infty/V_{Str})_{eff} \approx 0.2$

------ Without jet effect

——— With jet effect

Figure 6. Jet effect on $c_A = f_\alpha$
(Commas represent decimal points)

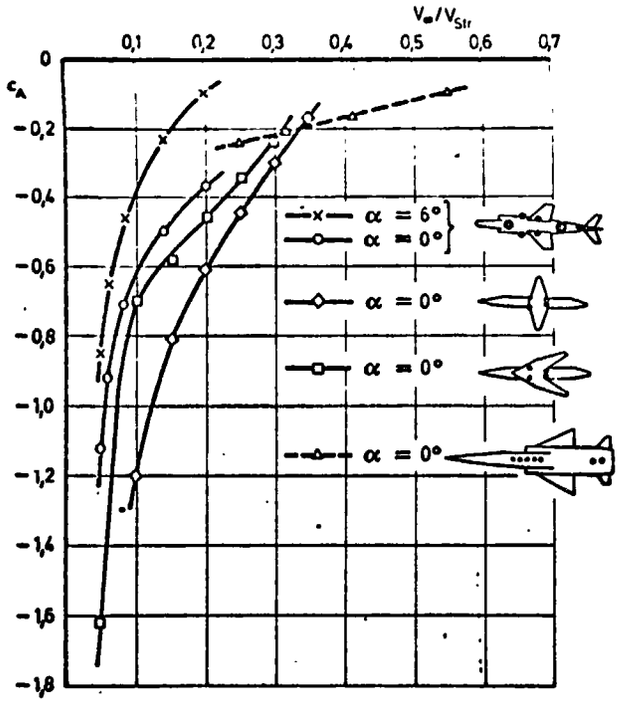


Figure 7. Jet effect in transition; $c_A = f(V_\infty/V_{Str})$
(Commas represent decimal points)

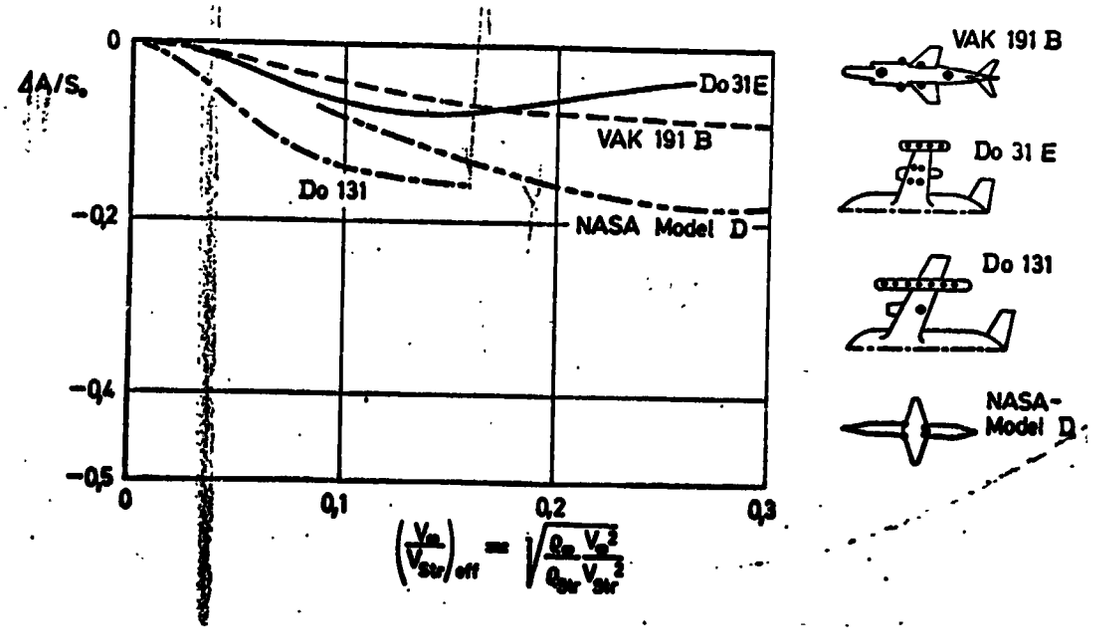


Figure 8. Lift reduction in transition from jet effect (wind tunnel measurements) according to [19]
(Commas represent decimal points)

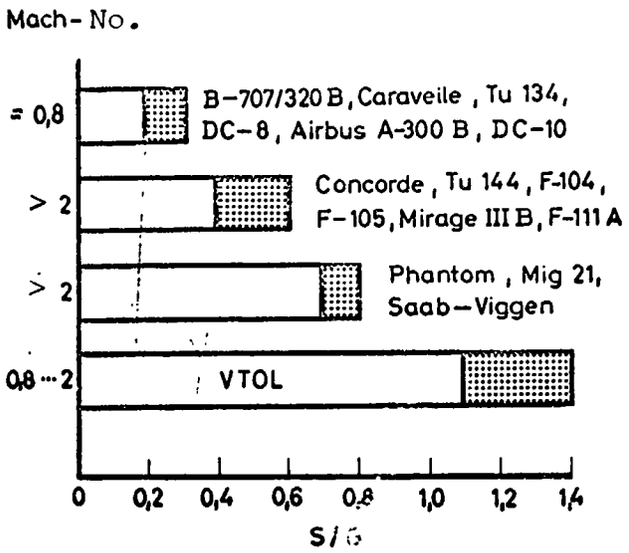
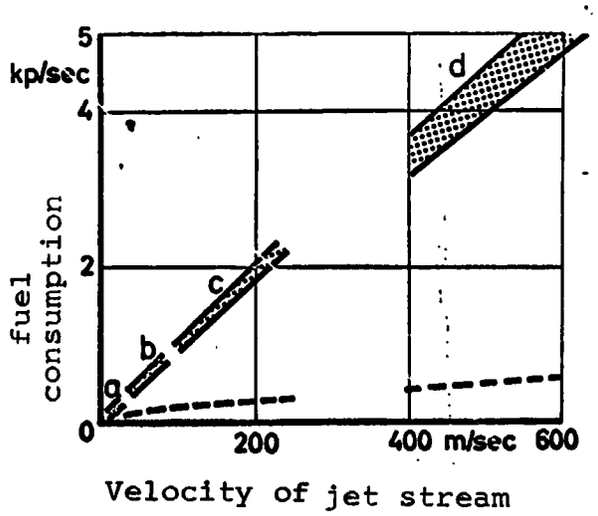
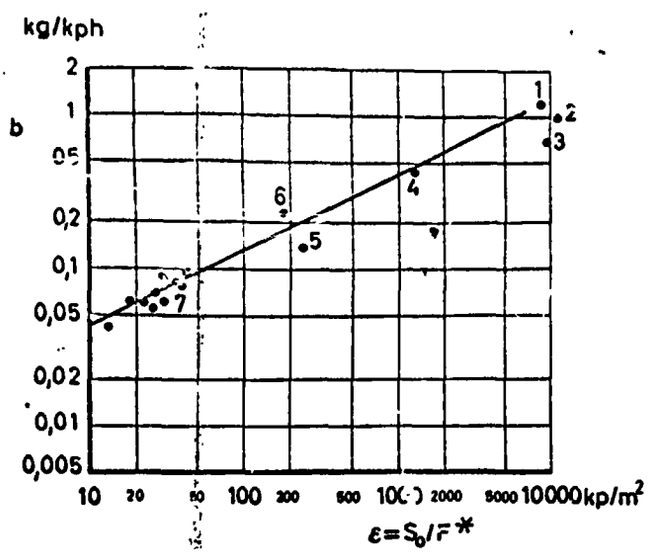


Figure 9. Reciprocal thrust load of given models
(Commas represent decimal points)



Hover using: a = rotors c = ducted fan
b = propellers d = turbojet and turbofan

Figure 10. Fuel consumption as a function of the velocity of the jet stream according to [27]



Model

1 Fiat G 95/4
2 VAK 191 B
3 P-1127
4 Ryan XV-5a
5 Hiller-Ryan XC-142 A
6 Curtiss-Wright X-19
7 Conventional helicopters

Figure 11. Specific fuel consumption as a function of the radiant area load according to [28]

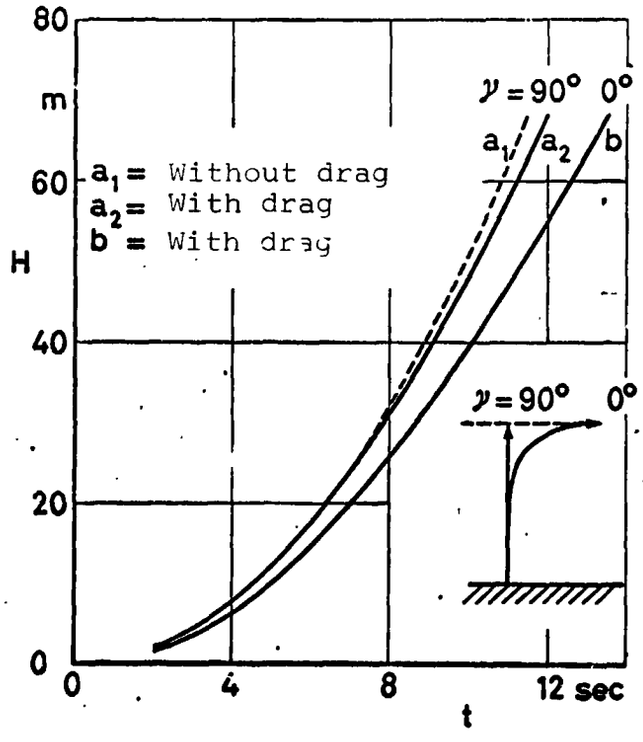


Figure 12. Effect of aerodynamic drag and angle of position on the take-off time according to [29]

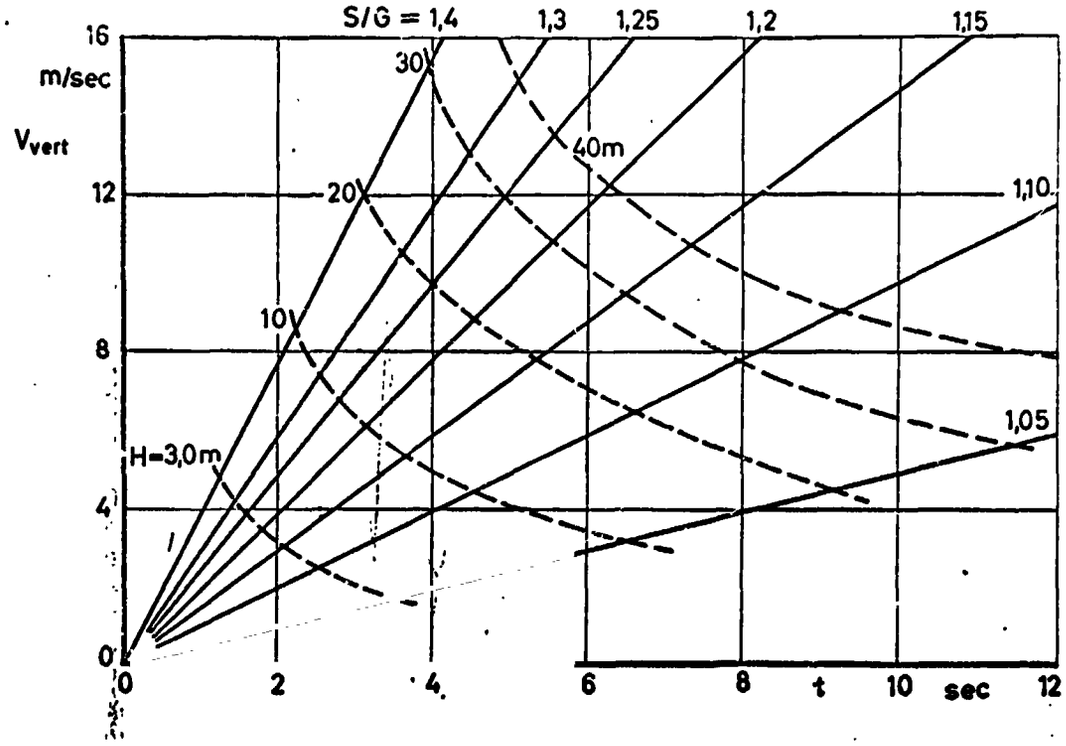
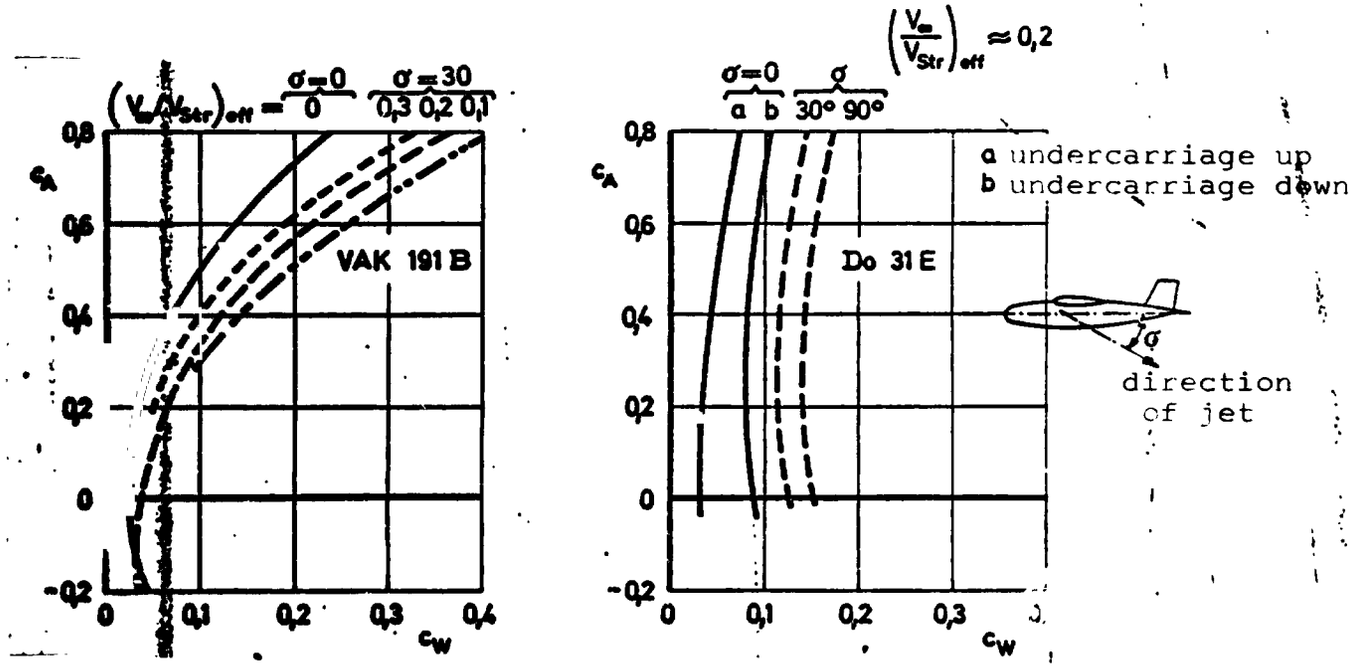


Figure 13. Relationship between reciprocal thrust load, climbing altitude and climbing time

(Commas represent decimal points)



——— Without jet ------- With jet effect

Figure 14. Aircraft polar curve with effect of jet stream
(Commas represent decimal points)

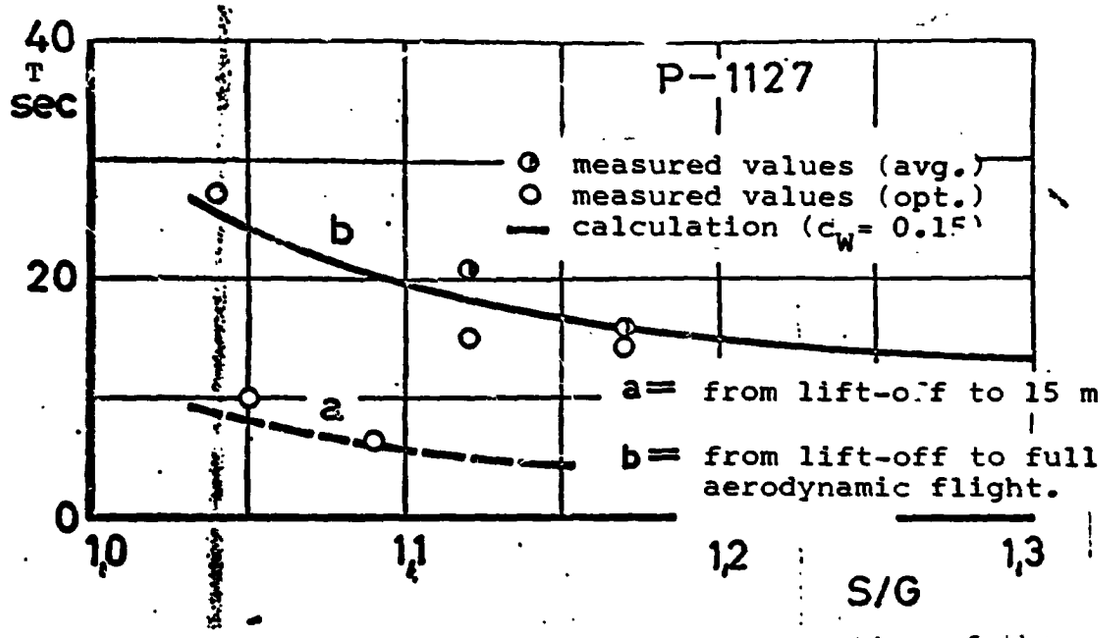


Figure 15. Take-off times as a function of the reciprocal thrust load for model P-1127.

(Commas represent decimal points)

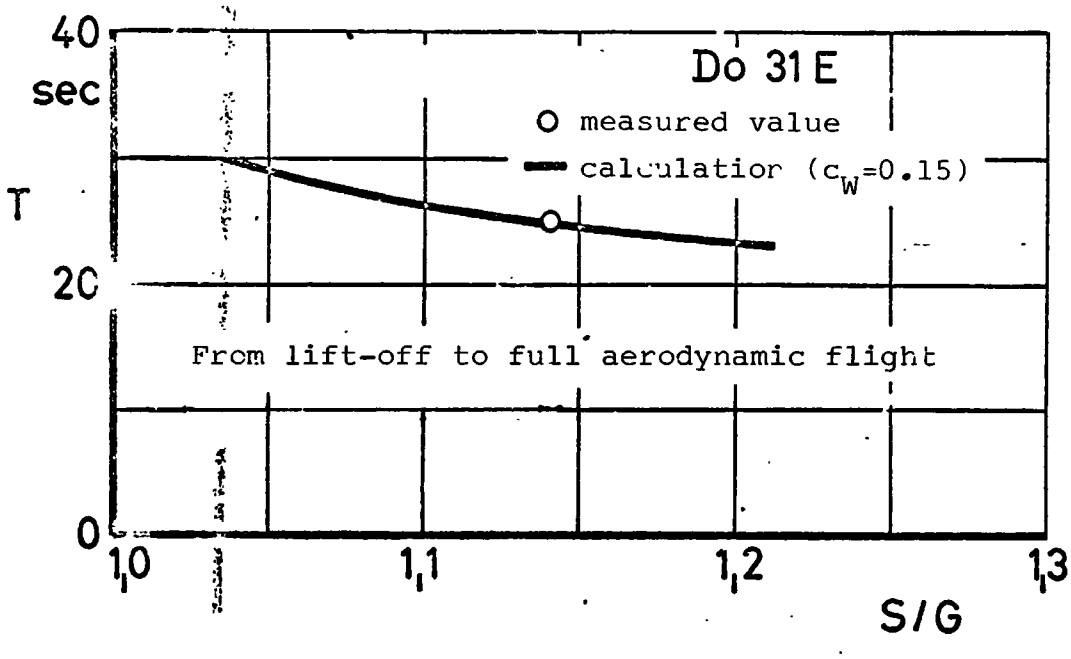


Figure 16. Take-off times as a function of the reciprocal thrust load for model Do 31 E

(Commas represent decimal points)

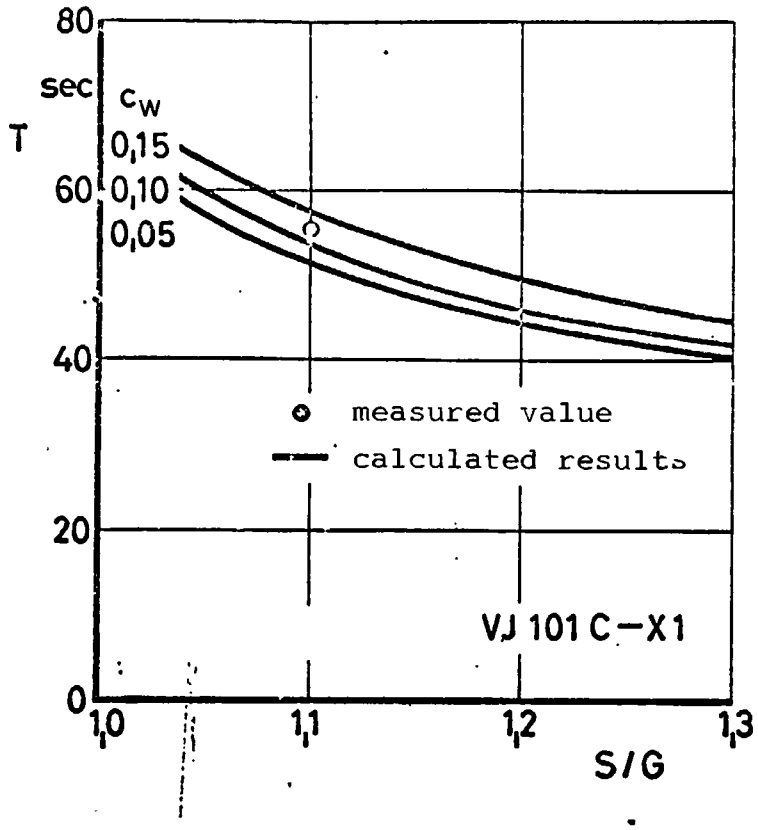


Figure 17. Take-off times as a function of the reciprocal thrust load for model VJ 101 C

(Commas represent decimal points)

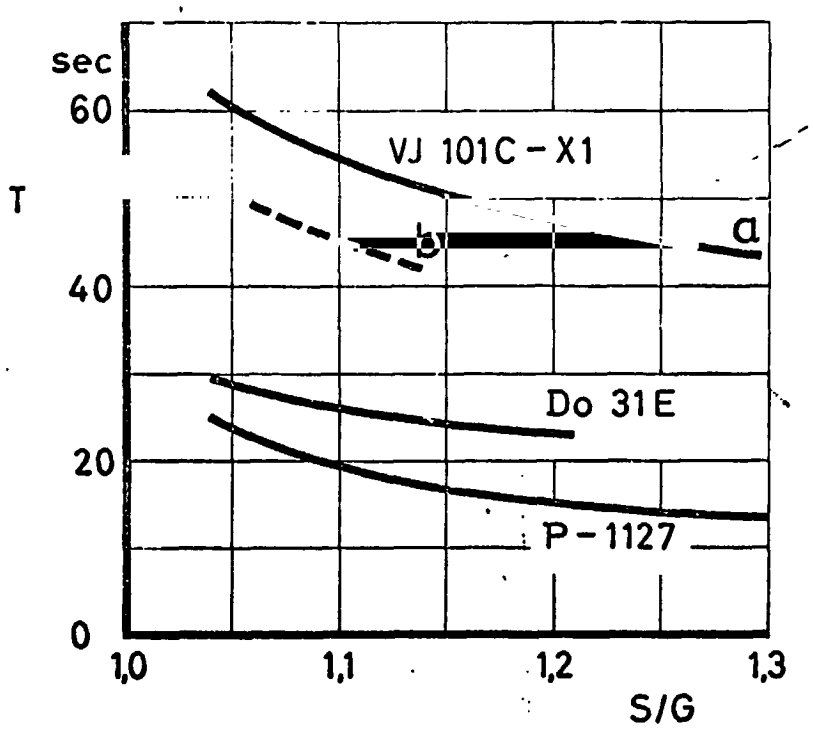


Figure 18. Comparison of transition times for VTOL-aircraft

Curve a: VJ 101 C with original rotation schedule according to [20]

Curve b: VJ 101 C with modified rotation schedule according to [34]

(Commas represent decimal points)

Measurement values

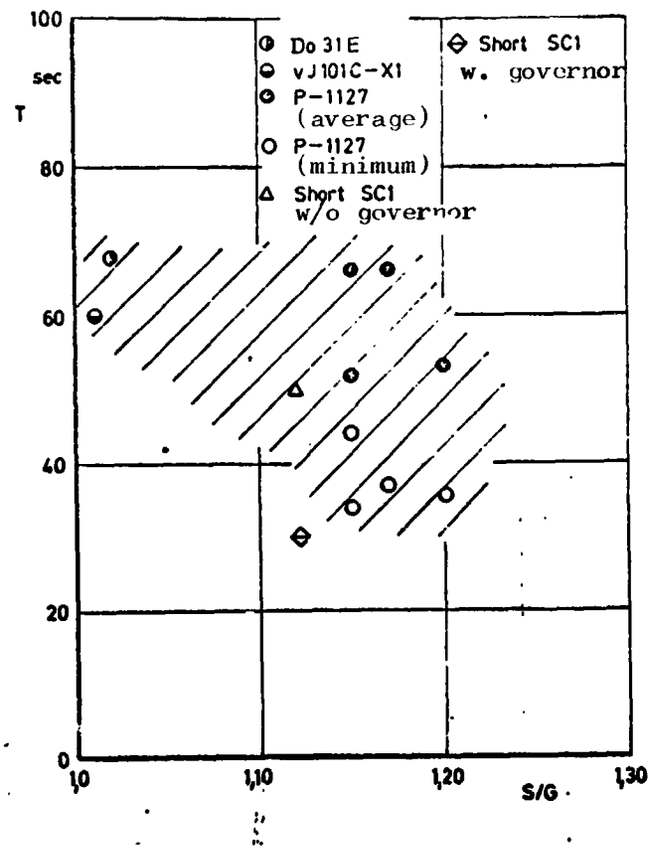


Figure 19. Measurement values for VTOL-aircraft

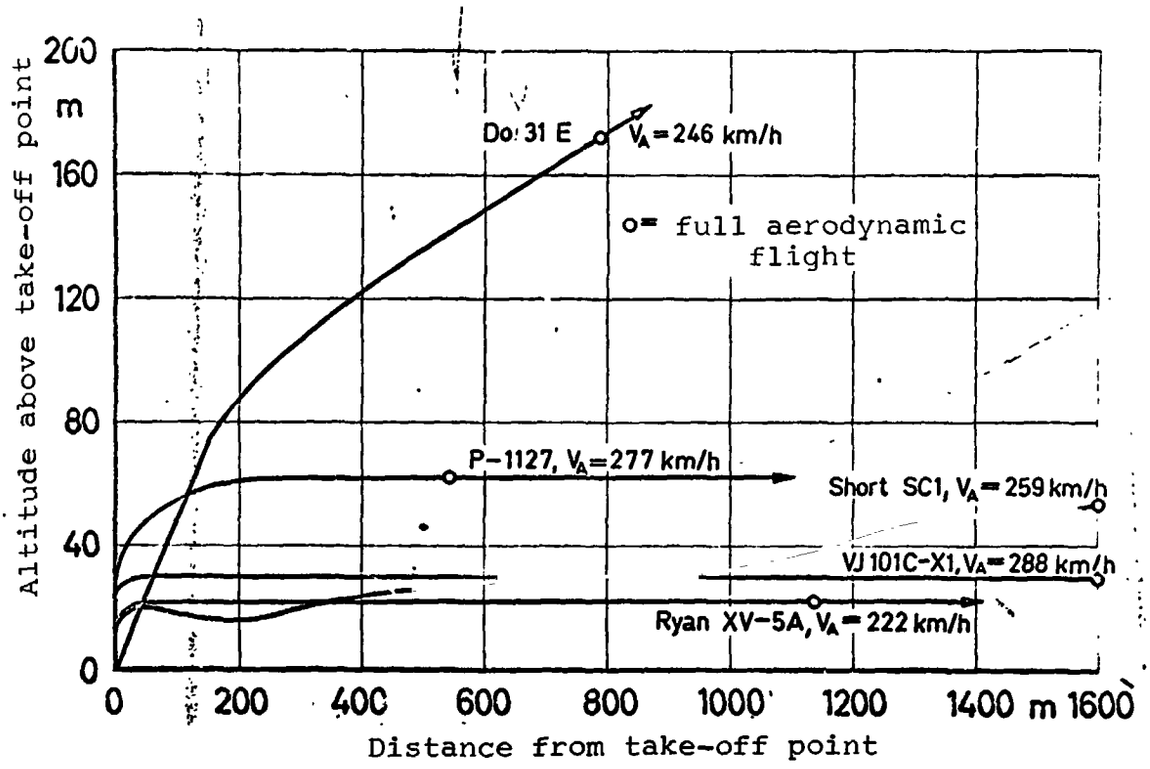


Figure 20. Flight path at take-off for VTOL-aircraft

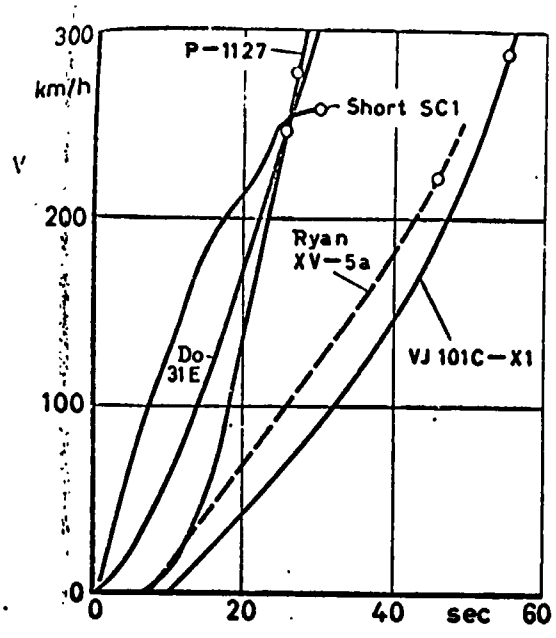
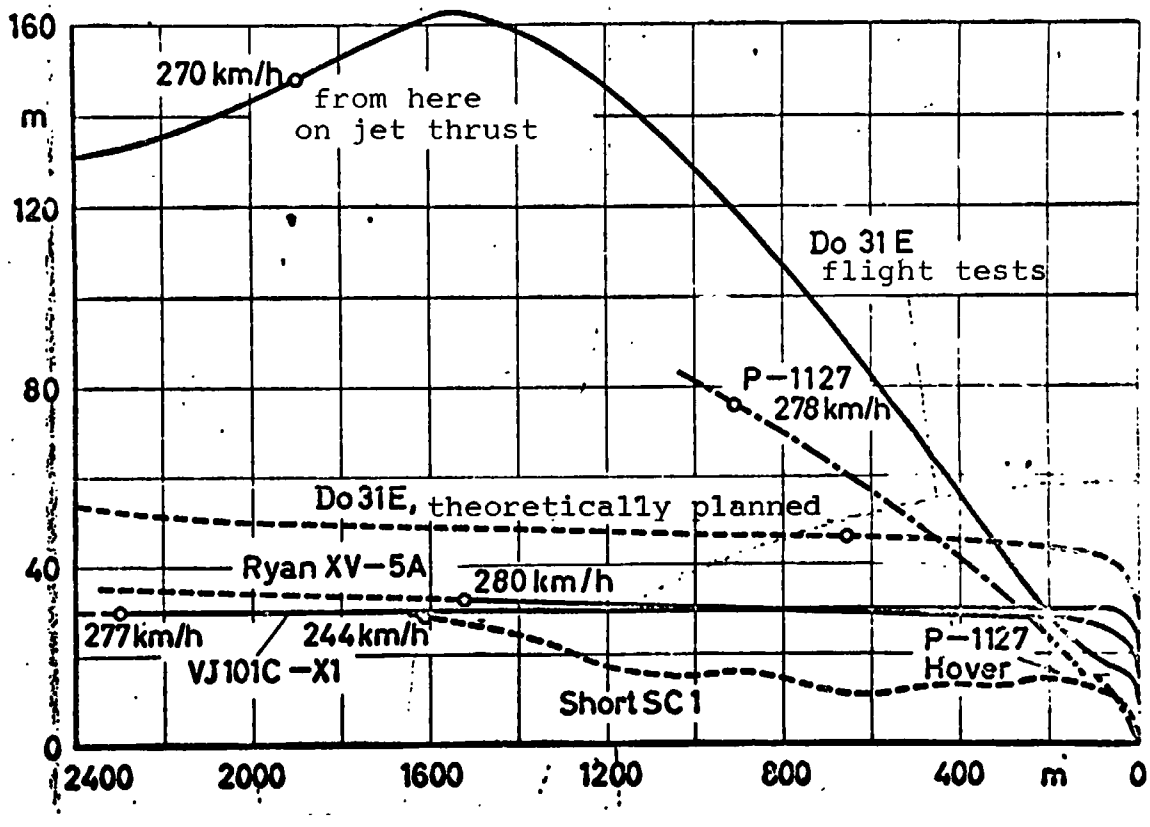


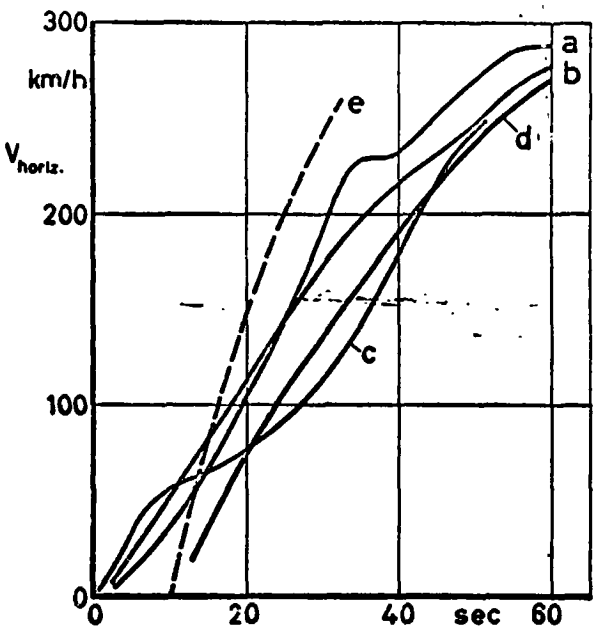
Figure 21. Velocity gradient at take-off

The circle indicates the point at which full aerodynamic flight is reached



Distance to landing point

Figure 22. Landing flight path for VTOL-aircraft



Model: a = P-1127
b = VJ 101 C-X1
c = Short SC 1
d = Do 31 E3
e = Do 31 E3
(theoretical optimum)

Figure 23. Decrease in speed during landing